

Integrated multi-objective optimization framework for urban water supply systems under alternative climates and future policy

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ABSTRACT

The sustainable implementation of an urban water supply system (UWSS) should achieve an optimum compromise among water ecosystem protection, climate change mitigation, and economic performance. This paper establishes an UWSS optimization framework by integrating a multi-objective optimization model with life cycle assessment and a water distribution system simulation model. The trade-offs among total cost, greenhouse gas (GHG) emission, and an extended water ecosystem impact (WII) objective are taken into consideration. The central area of Beijing City which is the main water-receiving area of the South-to-North Water Transfer Project (SNWTP), is chosen as a case study. A baseline scenario for 2012 and several future scenarios for 2020 and 2030 are implemented to investigate the influence of alternative climates and future policies on UWSS optimization. The outcome of this study indicates that the UWSS should be shifted towards an unconventional water-based supply system in the future. The share of contribution of the unconventional water supply is increased from 41% in 2012 to more than 70% in 2020 and 2030. This result can be drawn in all of the water-receiving areas of the middle route of the SNWTP. Moreover, alternative climates have influences on unconventional water utilization. Imported water through the middle route of the SNWTP is a preferable choice to augment the water supply in arid climates while reclaimed wastewater is more appropriate in moist climates. A decomposition analysis of the emissions reduction policies shows that the water demand control strategy is efficient in GHG emissions reduction while the water supply management strategy is efficient in WII reduction. Such a systematic analysis of an UWSS could provide sustainable and practical recommendations on water resource management in arid regions.

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1. Introduction

Over the last few decades, climate change and anthropogenic activities have intensified water scarcity in many parts of the world (Hejazi et al., 2015). To meet this challenge, alternative water resources such as reclaimed wastewater, desalinated seawater and imported water have been widely introduced to augment water supplies (Mo et al., 2014). For example, wastewater reuse is rapidly developing in the United States, Western Europe, Australia, Israel and China (Paton et al., 2014); seawater desalination project is approaching exponential growth, especially in coastal regions

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(Dolnicar and Schaefer, 2009). Meanwhile, water transfer project has been adopted worldwide with remarkable function to relieve regional water shortage and balance heterogeneous distribution of water resource (Wei et al., 2010). The North China Plain, bounded by the Hai, Huai, and Yellow River holds 33% of the total population and 40% of the total cultivated land, yet it only shares 7.7% of the national water resources (Cheng et al., 2009). To alleviate water shortage in the North China Plain, the South-to-North Water Transfer Project (SNWTP) has been established and is supposed to be fully implemented by 2050 with a total transfer capacity of 44.8 billion m³/year (Zhao et al., 2015). Since unconventional water resources play an increasingly important role in urban water supply, there is a need to develop a sustainable urban water supply system (UWSS) integrating unconventional water resources with conventional water resources.

Making decisions about a sustainable UWSS involves numerous considerations, such as water supply security, economic cost,

energy consumption, and ecological protection (Farooqui et al., 2016). These objectives are not independent and need to be balanced and negotiated (Reed et al., 2003). The application of multiobjective optimization techniques has been widely reported in water resources planning and management. Nondominated sorting Genetic algorithm II (NSGA II) is one of the most efficient and popular evolutionary algorithm to find optimal solutions for optimization problems, especially in the field of water resources management (Reed et al., 2013). Matrosov et al. (2015) used NSGA II to reveal the trade-offs among costs, system resilience, engineering and environmental metrics in planning a real-world water resource system. Penn et al. (2013) presented the optimal distribution of greywater reuse in an existing municipal sewer system with consideration of the system cost and momentary wastewater velocity in the sewer pipes. Zhang et al. (2014) investigated the optimal wastewater reuse allocation for 31 provinces of China considering the trade-offs among wastewater reuse supplies and demands, costs and profits, as well as pollutants reduction. Furthermore, a number of studies have considered incorporating nontraditional water sources into UWSS to optimize water resource management. For example, Abdulbaki et al. (2017) developed an optimization model for the multiple water allocation taking into account the spatially distribution of water supply and demand nodes. García-Montoya et al. (2016) presented optimization formulation for designing residential water networks involving harvested rainwater and reclaimed wastewater with consideration of the economic, environmental, and fresh-water objectives.

These previous studies typically focus on evaluating the trade-off among supply reliability, economical cost, and GHG emissions in sustainable water management. Natural water ecosystem is rarely included in the system boundaries of water system optimization, and the water availability has been simply considered as a physical constraint in an optimization model. To address the sustainability of water system, a new urban water paradigm, called integrated urban water management (IUWM) has emerged and been accepted globally over the last two decades (Chu et al., 2015). The principles of IUWM emphasized that the entire urban water cycle, including natural and anthropogenic, should be considered as an integrated system in water system planning and design (Mitchell, 2006). Furthermore, previous studies have demonstrated that the system boundaries have a significant influence on the results of water system evaluation (Lam et al., 2017). Therefore, water ecosystem impacts derived from anthropogenic water flow, taking into account both the quantity and quality of water withdrawn and returned into the environment, should be integrated into UWSS optimization.

In addition, decision-making in water management for future development widely involves uncertainty (Safavi et al., 2016). Recently, the UWSS have become more challenging due to both increased uncertainty of climate change and community changes (Mortazavi-Naeini et al., 2014). A number of studies have examined the potential effects of climate change on water resources management and evaluated water system performance in extreme weathers. Paton et al. (2013) presented a scenario-based sensitivity analysis to assess the impacts of climate change on water supply security. Ren et al. (2017) developed a multi-objective model for simultaneously optimizing the use of water and land resources for irrigation under the variations of rainfall and evapotranspiration. Xu et al. (2016) proposed an optimization method for water transfer and allocation in drought conditions. However, the impact of policy implementations (i.e., alternative water supply strategies, leakage control, water demand management, and so on) on an UWSS optimization has rarely been considered in previous studies. Considering that policies have an important effect on future water system development (Loubet et al., 2016), there is a need to

optimize an UWSS with considerations of alternative climates and future policy implementations.

Therefore, the aim of this study is to establish an UWSS optimization framework for alternative water resources configuration, considering the trade-offs among total cost, life-cycle GHG emissions, and an extended water ecosystem objective. It combines the use of multi-objective optimization, life cycle assessment, and a water distribution system simulation model. The framework is applied to the central area of Beijing City, which is the main water receiving area of the middle route of the SNWTP. A baseline scenario for 2012 and several future scenarios for 2020 and 2030 are implemented to investigate the potential effects of alternative climates and future policies on the UWSS optimization. Our previous study covered a life cycle assessment for unconventional water supply alternatives in typical water-receiving areas of the SNWTP. This paper is a follow-up of our earlier study and fills in an important gap in incorporating imported water through the SNWTP into an existing water supply system to optimize multi-source water allocation among water sectors. The main contribution of this work is a demonstration of a holistic UWSS optimization framework with extended indicators of interest to water managers and urban planner, taking into account the potential impact of future trends on an UWSS optimization.

2. Methods

2.1. Urban water supply system

Fig. 1 shows the system boundaries for the overall UWSS that was considered in this study. It covers the processes associated with water abstraction from the sources, water treatment, water distribution through the network, and main activities relevant to water flow. Water sources include surface water, groundwater, imported water and reclaimed wastewater. System boundary of surface water, groundwater and reclaimed wastewater is the geographic boundary of city while imported water is abstracted from external regions. Since wastewater reclamation could generate environmental benefits by decreasing wastewater discharges and preventing pollution, the water ecosystem impacts derived from wastewater discharge were included in the system boundaries. End users within the urban system boundary are divided into household, public, industry, and agriculture use. Reclaimed wastewater is not considered to be allocated to the household sector since its applicability is rather limited in China (Zhang et al., 2014).

2.2. The framework of UWSS optimization

This work provides an UWSS optimization framework for estimating the optimum abstraction of water resources and their allocation among water sectors. It combines the usage of a multi-objective optimization algorithm, the life cycle assessment, and a water distribution system simulation model. The utilized multi-objective optimization algorithm was based on NSGA II developed by Deb et al. (2002). It is an effective method for multi-objective optimization because it can rapidly evolve an approximation of entire trade-off (Pareto) fronts of multiple objectives in a single run (Reed et al., 2013). The EPANET 2.0 simulation model was applied to develop a site-specific water balance model and check hydraulic constraints for the UWSS optimization (Perelman et al., 2015). The flowchart of the solution methodology is presented in Fig. 2.

2.2.1. Objective functions

In this study, three objective functions were formulated, i.e., minimum total cost (TC), minimum life-cycle GHG emissions, and

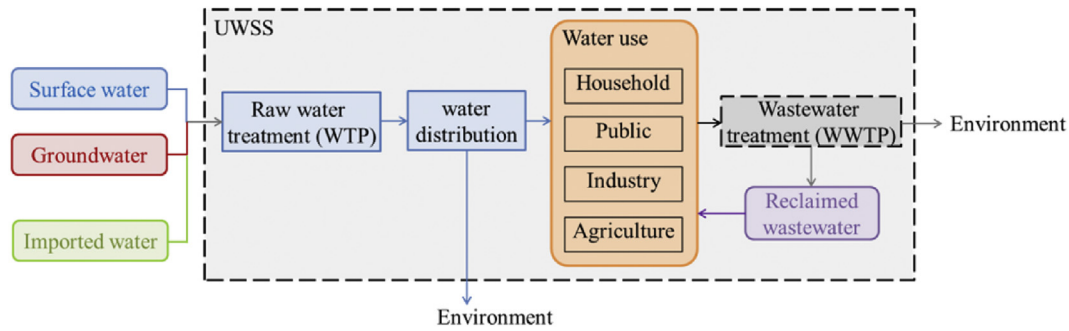


Fig. 1. The system boundaries of integrated urban water supply system examined in this study.

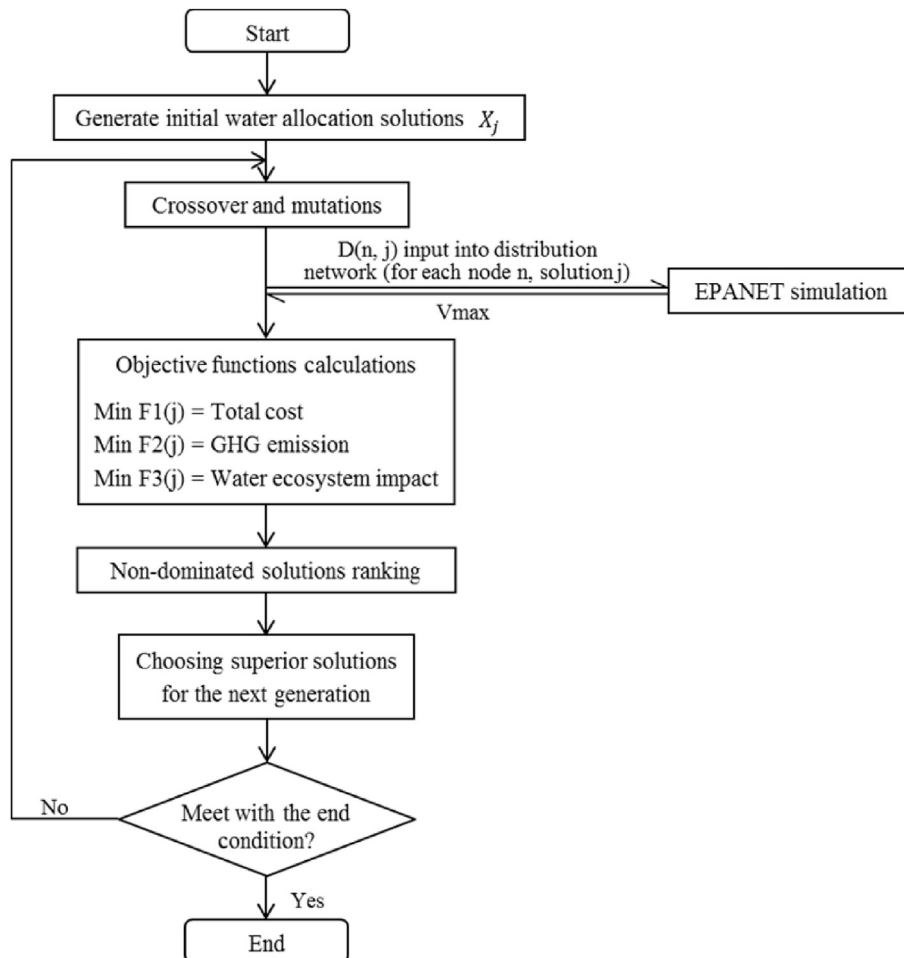


Fig. 2. Methodology flowchart.

minimum water ecosystem impact (WII).

The cost of an UWSS consists of two components: water production cost and water distribution cost. Both water production cost and water distribution cost contain capital cost, and operation and maintenance (O&M) costs. The calculation for cost minimization is presented in Equation (1).

$$\min Obj_c = \sum_{i=1}^4 PC_i + DC \quad (1)$$

$$PC_i = PCC_i + POC_i \quad (2)$$

Where i is alternative water resources, PC_i is the yearly cost for water production from source i (yuan), DC is the yearly cost for water distribution (yuan), PCC_i is the annualized capital cost for water production from source i (yuan) and POC_i is the yearly O&M costs for water production from source i (yuan). According to Newman et al. (2014), facility capacity is a predictor of capital cost of water production system, following a power law relationship. The total water treatment capacity depends on the maximum water demand (Bradshaw and Luthy, 2017). Therefore, the annualized capital cost for water production from source i (PCC_i) is calculated using Equation (3). The O&M costs, which contain charge on water

resources, energy and chemical cost for water abstraction and treatment, labor and maintenance cost, linearly with the total water supply. The yearly O&M costs for water production from source i (POC_i) is presented in Equation (4).

$$PCC_i = a_i \cdot C_i^{b_i} \cdot \frac{\theta \cdot \sum_{k=1}^4 q_i^k}{C_i} \cdot \frac{r(1+r)^t}{(1+r)^t - 1} \quad (3)$$

$$POC_i = \sum_{k=1}^4 UPOC_i \cdot q_i^k \quad (4)$$

Where a_i is the cost curve coefficient for capital cost of water production system with source i , b_i is the cost curve exponent for capital cost of water production system with source i , C_i is the treatment capacity of a water production system with source i (m^3 /year), $\theta \cdot \sum_{k=1}^4 q_i^k$ is the maximum yearly water supply from source i (m^3 /year), θ is the peaking factors applied to the peak daily flows, q_i^k is the average yearly water supply from source i to user k (m^3 /year), $(r(1+r)^t)/(1+r)^t - 1$ is capital recovery factor, r is the discount rate, t is the life span of the project (year), and $UPOC_i$ is O&M costs for unit volume of water production from source i (yuan/ m^3).

The calculation for the life-cycle GHG emissions minimization is presented in Equation (5).

$$\min Obj_{em} = \sum_{i=1}^4 \sum_{k=1}^4 (PE_i + DE) \cdot q_i^k \quad (5)$$

Where PE_i is the life-cycle GHG emissions of unit volume of water production from source i (kg CO_2 -eq/ m^3), DE is the life-cycle GHG emissions of unit volume of water distribution (kg CO_2 -eq/ m^3). All the emissions embodied in materials, chemicals and electricity consumed for water production and distribution were included in the life-cycle GHG emissions analysis. In this study, it was assumed that all of the water sectors obtained tap water through the water distribution network. In addition, electricity consumption for per unit of reclaimed wastewater distribution is similar to that of tap water (Zhou et al., 2013). The electricity consumption for water distribution was calculated by multiplying the average electricity consumption for unit volume water distribution by the total quantity of water distribution.

To emphasize the impact of anthropogenic water flow (i.e., natural water resources extraction and wastewater discharge) on the natural water ecosystem, the method described in Bayart et al. (2014) was adopted and modified to assess water ecosystem impact (WII) of an UWSS. Both consumptive water use and degradative water use were considered in the WII evaluation. The third objective function, i.e., minimization of the WII of an UWSS, is shown in Equation (6).

$$\min Obj_{WII} = \sum_{i=1}^2 \sum_{k=1}^4 (q_i^k \cdot wq_i \cdot WSI_i) - \left(W_e - \sum_{k=1}^4 q_4^k \right) \cdot wq_e \cdot WSI_1 \quad (6)$$

$$wq_i = \min_{p} \left(1; \frac{Cref_p}{C_{ip}} \right) \quad (7)$$

Where wq_i is quality index of water withdrawn from source i , WSI_i is water scarcity index of source i , W_e is secondary effluent from wastewater treatment plant (m^3 /year), wq_e is quality index of secondary effluent from wastewater treatment plant, $Cref_p$ is

reference concentration for pollutant 'p', corresponding to ambient water quality standards for surface water/groundwater in China (mg/L), C_{ip} is effective concentration of pollutant 'p' in the water withdrawn from source i (mg/L).

For water quality index (wq_i) accounting, the critical pollutant, nitrogen (N), phosphorus (P), and chemical oxygen demand (COD) in the water body were evaluated. Since different pollutants can be diluted by water at the same time, the minimum value of $Cref_p/C_{ip}$ was adopted in this study (Zeng et al., 2013).

2.2.2. Physical constraints

The amounts of water demand, water availability, water supply infrastructure capacities, water balance and hydraulic constraints were considered in the UWSS optimization. The model's constraints are presented as follows:

$$D_k \leq \sum_{i=1}^4 (1 - \gamma) q_i^k \quad (8)$$

$$\sum_{k=1}^4 q_i^k \leq A_i \quad (9)$$

$$\sum_{k=1}^4 q_i^k \leq S_i \quad (10)$$

$$q_4 = 0 \quad (11)$$

$$\sum_{l \in \phi} Q_{ln} + d_n = 0 \quad (12)$$

$$P_0 \geq P_{min} \quad (13)$$

$$0 \leq V_l \leq 2.5 \quad (14)$$

Where D_k is water demand of user k (m^3 /year), γ is the leakage ratio of water supply, including water lost in waterworks and distribution pipelines, A_i is water resource availability of source i (m^3 /year), S_i is the total water supply infrastructure capacities with source i (m^3 /year), d_n is water demand of node n in water distribution network (m^3 /d), $\sum_{l \in \phi} Q_{ln}$ is the water inflow and outflow to

node n (m^3 /d), P_0 is the hydraulic pressure of the control node in water distribution network (Mpa), P_{min} is the minimum pressure required for water demand node (Mpa), V_l is the flow velocity of water in pipeline l in water distribution network (m/s).

Equations from (12) to (14) are water balance and hydraulic constraints, which were calculated by the EPANET 2.0 simulation model. Two water flow conditions were simulated, i.e., the average daily water flow condition and the peaking factor applied to the peak daily flow condition; the peaking factor was assumed to be 1.3. The simulation in EPANET was performed for three days and the simulation time step is 6 h. The results of the last day for each distribution were saved and taking into account the constraints. The flow velocities in pipes were calculated by solving the continuity and energy conservation equation for each link (Perelman et al., 2015). According to the Code for design of outdoor water supply engineering (GB50013-2006) (MCPRC, 2006), the flow velocity required for water in a distribution network is 0.6–1.4 m/s. For more flexibility in the optimization, the model constraint was set to 2.5 m/s.

2.3. Research site

The central area of Beijing City was chosen as a case study since it is the main water receiving area of the middle route of the SNWTP (Fig. 3). This region comprises a total of 12.28 million inhabitants and an area of 1368.3 km² (BMBS, 2013). The per capita freshwater resources in Beijing are 191 m³, which is much lower than the threshold of water scarcity in the world (i.e., 500 m³ p.a.) (BWA, 2012). To alleviate water shortage, alternative water resources have been introduced in this region, and play an increasingly important role in water supply. For example, in 2012, reclaimed wastewater represented 21% of the total water supply in Beijing, which even higher than local surface water supply (BWA, 2012). Meanwhile, the first phase of the middle route of the SNWTP was completed and placed in operation by December 12th, 2014. During the past two years, a total of 1.32 billion m³ of water was delivered to Beijing (IOBM, 2016).

2.4. Scenario design

A baseline scenario for 2012 and several future scenarios for 2020 and 2030 were implemented to highlight the influence of alternative climates and future policies on the UWSS optimization.

2.4.1. Baseline scenario

The availability of alternative water resources and the specific water demand for each water sector are shown in Table 1. Secondary effluent of wastewater treatment plants (WWTPs) is the water source of centralized reclaimed wastewater treatment plants (RWWTPs) in this region. Therefore, the availability of reclaimed

wastewater was determined by secondary effluent of WWTPs. Water demand by water sectors was determined by combining demographic and employment data from the Beijing Statistical Year Book (BMBS, 2013) and Beijing Water Resources Bulletin (BWA, 2012). The key parameters of the baseline scenario (S1) related to supplier, distribution and end users are presented in Table 2. In 2012, 10 water treatment plants (WTPs) with a total production of 1.172 billion m³/year and 9 RWWTPs with a total capacity of 0.410 billion m³/year were in operation in the research boundary. The details of the treatment capacities of WTPs and RWWTPs are provided in Tables S1 and S2 in the Supporting Information.

2.4.2. Future scenarios

Three short term scenarios for 2020 (S2–S4) and three middle term scenarios, for 2030 (M2–M4) were designed to investigate the influence of alternative climates and future policies on the UWSS optimization. Three alternative climates (i.e., normal, semi-arid, and arid) and various community changes based on future strategies (i.e., water treatment capacity, potential electricity grid mix changes and so on) were investigated in a scenario setting (Table 2). Values reported in the literature, government documents, the GaBi database, simulation model parameters, and estimation reasonings were used to gather the data.

The availabilities of water resources in future scenarios were estimated based on the uncertainty of climate change (Table 1). Scenarios S2 and M2 are set as normal climate conditions, scenarios S3 and M3 are set as semi-arid climate conditions, and scenarios S4 and M4 are set as arid climate conditions. The availabilities of surface water and groundwater in the normal, semi-arid, and arid climate condition were determined by 50%, 75%, and 95% confidence interval of the water resources of the so-called normal climate period (1956–2000), respectively (MWR, 2008). For imported water, the climate change in the water source area (i.e., southern China) and its impact on the quantity of water transferred were not considered in this study. Therefore, the availability of imported water is consistent.

3. Results and discussion

3.1. Optimal water allocation in baseline scenario

Fig. 4 presents the Pareto solutions for the baseline scenario. The objective values range from 6566.1 (solution 1) to 6574.1 (solution 2) million yuan/year for TC, 1189.6 (solution 1) to 1243.6 (solution 3) million kg CO₂-eq/year for GHG emissions, and 511.7 (solution 2) to 536.6 (solution 1) million m³ water-eq/year for WII (see more details in Table S3 in the Supporting Information). There was a clear trade-off between WII and TC objectives, as well as WII and GHG

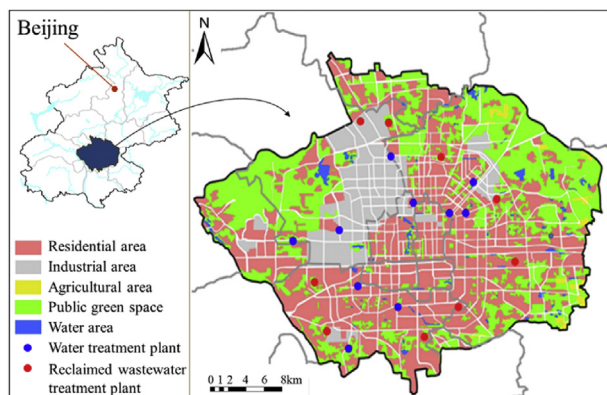


Fig. 3. General and detailed situation of the case study.

Table 1
Water resources and demands in the study area under different scenarios.

		Water availability (billion m ³ /year)				Water demand by sector (billion m ³ /year)			
		Surface water	Ground-water	Imported water	Reclaimed wastewater	Household	Industry	Public	Agriculture
Baseline scenario (2012) ^a	S1	1.80	2.16	0.28	0.940	0.950	0.164	0.235	0.01
Short term scenarios (2020)	S2	1.14 ^b	1.46 ^b	1.05 ^c	1.01 ^d	0.839	0.252	0.382	0.009
	S3	0.82 ^b	1.32 ^b	1.05 ^c	1.01 ^d	0.839	0.252	0.432	0.01
	S4	0.61 ^b	1.29 ^b	1.05 ^c	1.01 ^d	0.839	0.252	0.432	0.01
	M2	1.14	1.46 ^b	1.05	0.97	0.791	0.296	0.382	0.009
Middle term scenarios (2030)	M3	0.82	1.32 ^b	1.05	0.97	0.791	0.296	0.432	0.01
	M4	0.61	1.29 ^b	1.05	0.97	0.791	0.296	0.432	0.01

^a Data were collected from BWA (2012) and BMBS (2013).

^b Local water availability for future scenarios were estimated based on 50%, 75%, and 95% confidence interval of the water resources of the so-called normal climate period (1956–2000).

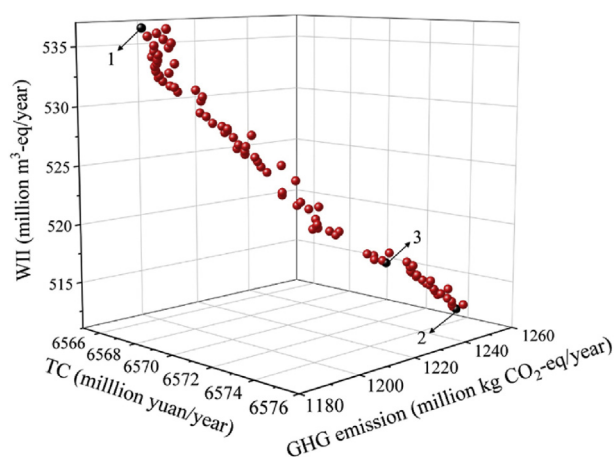
^c Data were collected from BMWDP (2008).

^d Data were estimated based on BCPLRMC (2016).

Table 2

Key parameters of baseline scenario and future scenarios.

		Baseline scenario (2012)	Short term scenarios (2020)	Middle term scenarios (2030)
		S1	S2–S4	M2–M4
Parameters related to supplier	Total capacity of WTPs ^a (billion m ³ /year)	1.172	1.964	2.700
	Total capacity of RWWTPs ^{b,c} (billion m ³ /year)	0.410	1.489	2.450
Parameters related to distribution	Water losses in DWD	17% ^d	10% ^e	8% ^e
Parameters related to users	Population (million)	12.28 ^b	10.84 ^e	10.84 ^e
	Per capita household water use (L/d)	212 ^b	212 ^e	200 ^e
	Gross value of industrial output (billion RMB Yuan)	110.43 ^b	193.71 ^e	296.15 ^e
	Water use intensity for industrial production ^{b,e} (m ³ /million RMB Yuan)	1500	1300	1000
	GHG emission by electricity consumption ^f (kg CO ₂ -eq/kWh)	0.965	0.726	0.695

^a Data were collected from BWG (2008).^b Data were collected from BMBS (2013).^c Data were collected from BJGOV (2012).^d Data were collected from BWA (2013).^e Data were collected from/estimated based on BCPLRMC (2016).^f Data were collected from NDRC (2016) and calculated based on GaBi database; The fossil fuel composition of electricity production is expected to be decreased to 60% in 2020 and to be decreased to 49% in 2030.**Fig. 4.** Pareto front obtained by integrated NASA II using the three-objective problems study for urban water supply system for baseline scenario. Note: WII is water ecosystem impact; TC is total cost.

emissions objectives. On the contrary, the objective of minimization of TC exhibited a positive correlation with the objective of minimization of GHG emissions. It means that optimal water supply systems that have higher costs are also likely to have a corresponding increase in GHG emissions. Similar results have been reported by Newman et al. (2014). This is due to the fact that most of the unconventional water sources are cost and GHG emissions intensive. For example, the GHG emission intensity of wastewater reclamation (1.08 kg CO₂-eq/m³) is much higher than that of tap water production from surface water (0.28 kg CO₂-eq/m³) and groundwater (0.41 kg CO₂-eq/m³). Moreover, the cost of water supply through the SNWTP is 6.92 yuan/m³, which is almost 3 times higher than that of the other water supply alternatives.

Since climate change draws worldwide attention and the study area is one of the driest regions in the world, the minimization of GHG emissions and WII were considered as the external sets of criteria. Therefore, solution 3 in Fig. 4 was selected as the control strategy as it has the minimization of WII (516.0 million m³ water-eq/year) and GHG emissions (1190.5 million kg CO₂-eq/year) in the obtained discrete approximation of the Pareto front. For the control strategy (solution 3), the conventional water supply ratio is 59%, which is lower than that reported in Beijing water resource

bulletin 2012 (Fig. 5). It indicates the potential of promoting a sustainable UWSS by the implementation of unconventional water supply. In addition, the optimal solution presented a 33% reduction in groundwater extraction but a 21% increase in surface water withdrawal compared with the current water supply pattern (BWA, 2012). The primary contribution to this result is the higher value of WII for groundwater than that for surface water. As mentioned in section 2.2.1., the objective of WII was determined by two parameters, i.e., the water scarcity index (WSI) and the water quality index (wq) of water source. The higher the value of the WSI, the more intense is the water scarcity; the higher the value of the wq, the better is the water quality. Although groundwater withdrawal has decreased in the past two decades in Beijing, the groundwater extraction rates far exceeded its recharge rates, leading to a high value of WSI for groundwater (Zeng et al., 2013). Meanwhile, the wq value of 0.62 for groundwater is higher than that of 0.48 for surface water (Zeng et al., 2013). It means that unit volume of groundwater utilization provokes a greater potential impact on the local water ecosystem than an equivalent surface water extraction. For the purpose of minimizing the local water ecosystem impact of an UWSS, it is reasonable to reduce groundwater usage. For nonconventional water resources, reclaimed wastewater and imported water through the SNWTP accounted for 24% and 17% of the total water supply, respectively (Fig. 5). It should be noted that the optimal utilization of imported water and reclaimed wastewater in the baseline scenario were restricted by the infrastructure capacities (Table 2).

For alternative water sources allocation among different sectors, imported water and reclaimed wastewater contributes 71–91% of the water supply for all water sectors, except for household user (Fig. 5). For the household sector, conventional water resources are responsible for more than 80% of its water demand. In fact, flushing and cleaning water accounts for approximately 13% of household water consumption, which means that part of the household water demand can be satisfied with low-quality water (Tao and Xin, 2014). However, reclaimed wastewater was not considered to be allocated to the household sector due to the limited applicability in China and the absence of a separate reclaimed wastewater distribution system for household users. In addition, the feasibility of the optimization schemes was identified by the EPANET 2.0 simulation model. The simulation of momentary diurnal velocity in the distribution system showed that all pipes meet the velocity requirement under both the average daily water flow condition and the

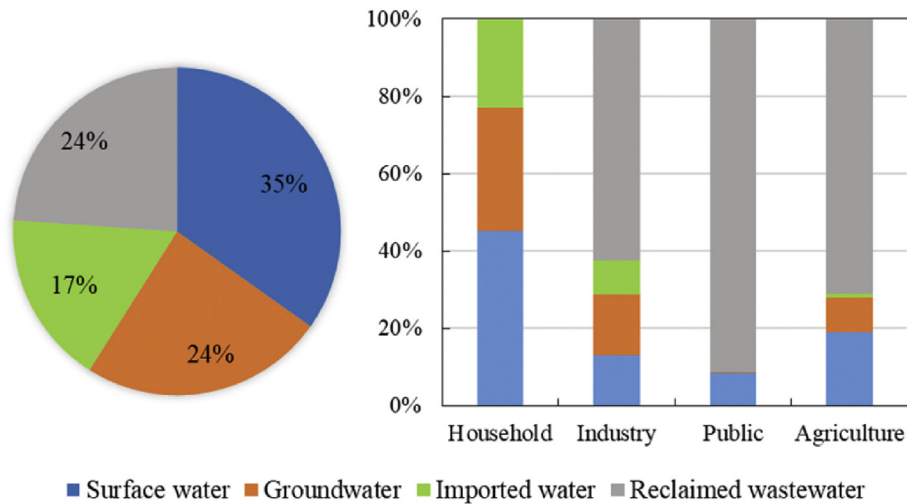


Fig. 5. Optimal extraction and configuration of alternative water resources for the baseline scenario.

peak daily flow condition (see more details in Fig. S1 in the Supporting Information).

3.2. Influence of policies implementation on future UWSS optimization

The Pareto optimal solutions for future scenarios are shown in Fig. S2 in the Supporting Information. According to the external sets of criteria, the solutions blackened at the Pareto fronts in Fig. S2 were selected as the control strategy and the corresponding performances of the UWSS for different future scenarios are shown in Table 3. The TC of the UWSS in the future scenarios is

8028.6–9396.6 million yuan/year, which is 22–43% higher than that in the baseline scenario. However, the UWSS in the future scenarios has less intensive GHG emissions and WII than that of the baseline scenario (Table 3). With a similar water demand, the UWSS in the future scenarios generates 10–16% lower GHG emissions than the baseline scenario. Meanwhile, WII of the UWSS decreased from 516.0 million m³ water-eq/year in the baseline scenario to 91.4–133.0 million m³ water-eq/year in the future scenarios. These environmental benefits are the synergistic effects of economic status, population growth, and various policy implementations including unconventional water supply augmentation, water demand management, grid mix change strategy and so on (Wan et al.,

Table 3
Performances of the urban water supply system under different scenarios. (million m³/year).

		Surface water	Ground- water	SNWTP	Reclaimed wastewater	Performance objectives		
						TC (million Yuan/year)	GHG emission (million kg CO ₂ -eq/year)	WII (million m ³ water-eq/year)
S1	Household	516.81	361.69	261.61	0	6571.9	1243.6	516.0
	Industry	25.8	30.94	17.99	123.27			
	Public	24.3	0.13	0.15	258.47			
	Agriculture	2.27	1.08	0.13	8.53			
S2	Household	263.56	140.66	503.62	0	9112.6	1026.5	133.0
	Industry	0.00095	0.00088	148.82	148.42			
	Public	0.0021	0.0012	97.14	291.12			
	Agriculture	0.0040	0.0019	5.73	16.24			
S3	Household	264.42	139.09	503.77	0	9332.9	1077.6	123.6
	Industry	0.00011	0.00079	139.24	157.79			
	Public	0.00061	0.0017	216.44	216.43			
	Agriculture	0.00015	0.00066	2.38	9.58			
S4	Household	263.04	140.52	503.71	0	9396.6	1067.8	119.7
	Industry	0.0029	0.00090	148.50	148.94			
	Public	0.0056	0.034	215.32	215.52			
	Agriculture	0.00064	0.017	5.73	5.66			
M2	Household	249.69	133.26	477.12	0	8028.6	1020.0	96.2
	Industry	0.0011	0.0010	174.88	174.41			
	Public	0.0021	0.0012	97.14	291.12			
	Agriculture	0.0040	0.0019	5.73	16.24			
M3	Household	250.50	131.77	477.25	0	8556.8	998.3	95.5
	Industry	0.00012	0.00092	163.62	185.42			
	Public	0.00061	0.0017	216.44	216.43			
	Agriculture	0.00015	0.00066	2.38	9.58			
M4	Household	249.19	133.12	477.20	0	8624.6	988.4	91.4
	Industry	0.0034	0.0011	174.51	175.02			
	Public	0.0056	0.034	215.32	215.52			
	Agriculture	0.00064	0.017	5.73	5.66			

2016).

To understand the extent of the contribution from each policy implementation to GHG emissions and WII reduction, the decomposition analysis method described in Wen et al. (2015) was applied to analyze emissions reduction policies under all scenarios. The baseline was set assuming no policy intervention and keeps the structure and technology the same as in 2012. As can be seen in Fig. 6, the total amount of GHG emissions reduction from implementing strategies ranges from 289.6 (scenario S2) to 444.2 (scenario M2) million kg CO₂-eq/year, and WII reduction ranges from 688.5 (scenario S2) to 847.6 (scenario M2) million m³ water -eq/year. It should be noted that strategies implementation presented a negative effect on GHG emissions reduction in the baseline scenario due to the wastewater reclamation augmentation. However, the augmentations of nonconventional water supply were the main contributors to WII reduction in all scenarios.

As can be seen in Fig. 6(a), all of the strategies except for wastewater reclamation augmentation have positive effects on GHG emissions reduction. The grid mix change strategy has a remarkable effect on GHG emissions reduction, accounting for more than 49% of the GHG emissions reduction in the future scenarios. To compare the water demand management strategies (i.e., industrial water use intensity control and household water saving appliance application) with the water supply management strategies (i.e., unconventional water supply augmentation and pipeline leakage control), the results showed that the former was more efficient in GHG emissions reduction than the latter. Approximately 10.9% and 33.6% of the total GHG emissions reduction were attributed to the water demand management strategies in 2020 and 2030, respectively. This proportion was supposed to reach about 75% in a previous study when taking into account the water-related GHG emissions associated with the end users (Lam et al., 2017). This is because residential water use, especially hot water use represents a significant portion of urban water-related GHG emissions (Bartos and Chester, 2014). However, considering that the purpose of this study is to establish an UWSS optimization framework for water allocation at a city scale, water-related GHG emissions associated with end users were excluded from the

system boundaries.

The WII reduction potential of alternative policies implementation is shown in Fig. 6(b). It can be seen that all of the policy implementations performed positive effects on local water ecosystem protection. Unconventional water supply augmentation has the excellent performance in alleviating local water ecosystem impacts, accounting for more than 75% of the total WII reduction in all scenarios. On the other hand, the WII reduction derived from water demand control strategies is less than 10% of the total WII reduction. This benefit is supposed to shrink due to the limited potential of water conservation. It demonstrates that unconventional water resources are significant in urban water system, not only for water supply ensuring but also for local ecosystem protection. Fig. 6 shows the emissions reduction and WII reduction under normal climate scenarios. In semi-arid and arid climate scenarios, the results of GHG emissions reduction and WII reduction for a particular applied policy are similar with the normal climate scenarios (Fig. S3).

3.3. Influence of alternative climates on future UWSS optimization

The optimal water supply schemes in future scenarios are shown in Fig. 7. Compared to the baseline scenario, it is evident that the UWSS shifts from a conventional water-based supply system to an unconventional water-based supply system in the future. The share of contribution of unconventional water supply increased from 41% in 2012 to more than 70% in 2020 and 2030. It is important to note that the result is applicable to all of the water-receiving areas of the middle route of the SNWTP. According to Equation (6) in section 2.2.1, the WII reduction potential of unconventional water supply is positively correlated with the water scarcity index of the regions. Considering that all of the water-receiving areas of the middle route of the SNWTP show severe to extreme water stress ($WSI = 0.6-1.0+$) (Zhao et al., 2015), the performance of unconventional water supply is similar in these regions in terms of WII reduction. In addition, the performance of the imported water supply in other water-receiving areas of the SNWTP is better than that in Beijing from the GHG emission perspective (Li et al., 2016).

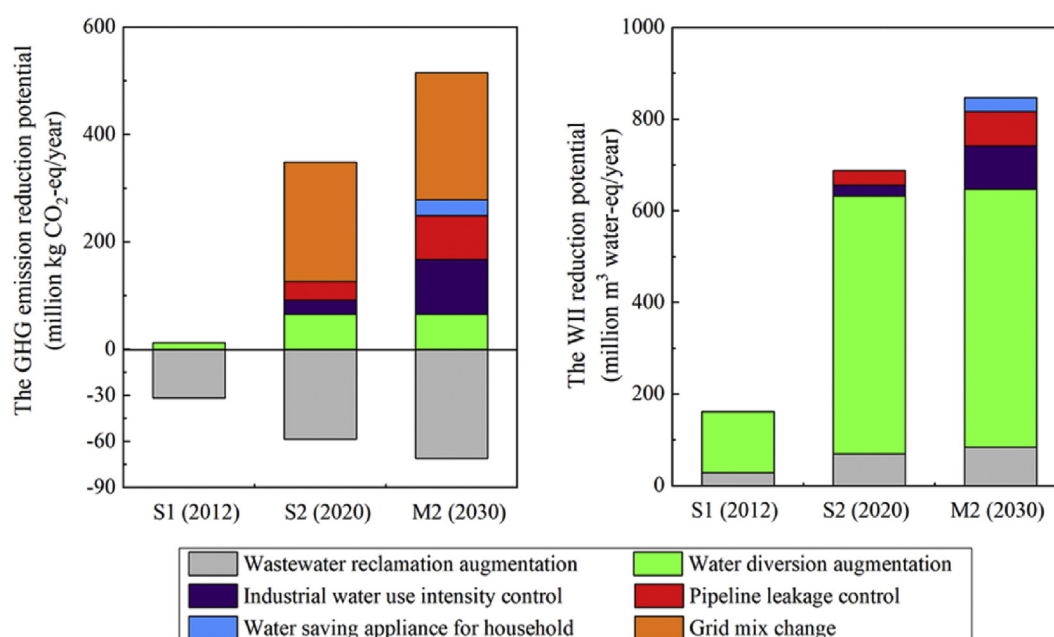


Fig. 6. Decomposition of the emission reduction policies under normal climate scenarios. (a) GHG emission reduction potential; (b) WII reduction potential.

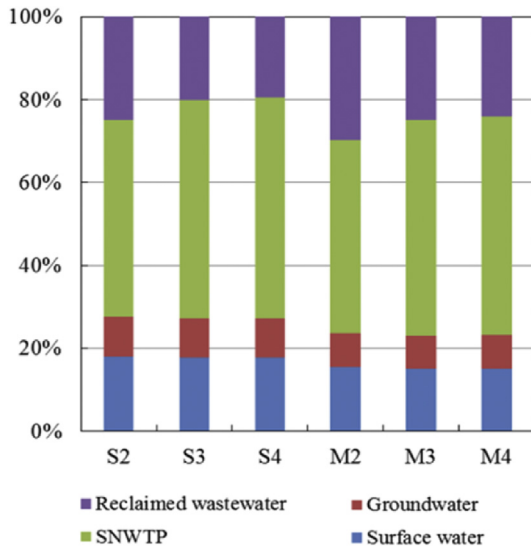


Fig. 7. Multi-source water configuration among water sectors under various future scenarios. Note: scenarios S2, S3, and S4 are short term scenarios for 2020; scenarios M2, M3, and M4 are middle term scenarios for 2030.

Since the performance of unconventional water supply in other water-receiving areas of the SNWTP is similar to or better than that in the study area, the result can be drawn in all of the water-receiving areas of the middle route of the SNWTP.

The amounts of conventional water supplies showed a small variation under different future scenarios, whereas alternative climates have an influence on the amounts of unconventional water supplies (Fig. 7). For example, water supplied by imported water through the SNWTP in scenario M2 (754.9 million m³/year) was lower than that in scenario M3 (859.7 million m³/year) and scenario M4 (872.8 million m³/year). Conversely, reclaimed wastewater supplied in scenario M2 (481.8 million m³/year) was higher than that in scenario M3 (411.4 million m³/year) and scenario M4 (396.2 million m³/year). The results imply that the imported water is a preferable choice for augmenting the water supply in arid climates while reclaimed wastewater is more appropriate in moist climates in the study area. This is because the WII reduction potential of imported water supply (0.84 m³ water-eq/m³) is higher than that of wastewater reclamation (0.54 m³ water-eq/m³).

3.4. Sensitive analysis

The sensitivity analysis was conducted to assess the robustness of the results in response to the variation that may occur to the water supply sources availability and water demand. This

sensitivity analysis was conducted in scenario M2 and two variances of imported water availability and four variances of water demand volumes were considered for sensitivity analysis. As can be seen in Table 4, the changes in the imported water availability and household water demand presented the most significant influence in water allocation. The −30% variance in imported water availability significantly increased the local water consumption. Water supplied from surface water and groundwater to sectors were changed by a maximum of 39.8% and 14.8%, respectively. Conversely, the resulting range for the water supplied from the surface water and groundwater to all water sectors varied between 0 and −55.0% in response to the 30% variance in imported water resource availability. The 30% variance in household water demand resulted in 61.0% and 25.0% increase in surface water and reclaimed wastewater use, respectively, however, the imported water consumption displayed little variation. Therefore, the local water resources availability, regional household water demand and the variation of the imported water availability are critical for the sustainable water supply system development.

4. Conclusions

In this study, a framework for optimizing an urban water supply system was developed and demonstrated in the central area of Beijing City. The framework combines the usage of a multi-objective optimization algorithm, the life cycle assessment and a water distribution system simulation model. The trade-offs among total cost, life-cycle GHG emissions, and water ecosystem impact are taken into consideration. To investigate the impact of alternative climates and future policies on the UWSS optimization, a baseline scenario (2012) and six future scenarios were implemented. The result shows that the UWSS should be shifted from a conventional water-based supply system to an unconventional water-based supply system in the future. This result can be drawn in all of the water-receiving areas of the middle route of the SNWTP. Moreover, alternative climates have influences on unconventional water utilization. Imported water through the middle route of the SNWTP is the preferable choice to augment the water supply in arid climates, while reclaimed wastewater is more appropriate in moist climates. With a similar water demand to the baseline scenario, GHG emissions and WII of the UWSS have decreased in the future due to various future policy implementations. A comparison between the water demand control strategies and the water supply management strategies shows that the former is efficient in GHG emissions reduction while the latter is efficient in WII reduction (i.e., local water ecosystem protection). Such a systematic analysis of an UWSS provides general recommendations on sustainable water resource management in water scarce regions.

Table 4

The relative changes of the results through sensitivity analysis for selected parameters.

	Variance	Relative change (%)															
		q_1^1	q_1^2	q_1^3	q_1^4	q_2^1	q_2^2	q_2^3	q_2^4	q_3^1	q_3^2	q_3^3	q_3^4	q_4^2	q_4^3	q_4^4	
<i>Supply side</i>																	
Imported	+30%	−19.5	0.0	−10.2	−10.0	−55.0	10.0	−40.0	−10.0	25.7	10.4	10.9	0.0	−10.6	−2.8	0.0	
	−30%	39.8	27.3	19.0	25.0	14.8	10.0	0.0	0.0	−25.2	−62.1	−74.5	−10.5	65.1	23.7	4.7	
<i>Demand side</i>																	
Household	+30%	61.0	−36.4	42.9	25.0	−10.0	−10.0	50.0	31.6	26.0	−34.1	−62.9	−56.4	32.4	20.2	33.0	
Industrial	−30%	15.0	−17.0	−10.0	11.4	10.0	−26.0	−23.7	0.0	−10.0	26.5	0.0	0.0	−40.0	6.7	0.0	
Public	+30%	10.0	−12.1	34.0	−20.0	−20.0	48.8	−11.0	18.0	0.0	−6.4	13.0	−26.7	10.0	7.0	0.0	
Agricultural	+30%	−3.8	−20.0	0.0	34.0	0.0	0.0	−10.0	−4.0	2.2	5.7	0.0	0.0	1.6	0.8	32.0	

Note. q_i^k is the water supply from source i to water sector k . $i = 1-4$ respectively represent surface water ($i = 1$), groundwater ($i = 2$), imported water ($i = 3$), and reclaimed wastewater ($i = 4$); $k = 1-4$ respectively represent domestic ($k = 1$), industry ($k = 2$), public ($k = 3$), and agriculture ($k = 4$) use.

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List of Abbreviations

Technologies/Users designation

GHG	greenhouse gas
IUWM	integrated urban water management
NSGA II	non-dominated sorting genetic algorithm II
RWWTPs	reclaimed wastewater treatment plants
SNWTP	South-to-North Water Transfer Project
TC	total cost
UWSS	urban water supply system
WII	water ecosystem impact
WWTPs	wastewater treatment plants
WTPs	water treatment plants

Variables and parameters

A_i	water resource availability of source i , m^3/year
a_i	cost curve coefficient for capital cost of water production system with source i
b_i	cost curve exponent for capital cost of water production system with source i
C_i	treatment capacity of a water production system with source i , m^3/year
C_{ip}	effective concentration of pollutant 'p' in the water withdrawn from source i , mg/L
C_{refp}	reference concentration for pollutant 'p', corresponding to ambient water quality standards for surface water/groundwater in China, mg/L
DC	yearly cost for water distribution, yuan
DE	life-cycle GHG emissions of unit volume of water distribution, $\text{kg CO}_2\text{-eq}/\text{m}^3$
D_k	water demand of user k , m^3/year
d_n	water demand of node n in water distribution network, m^3/d
i	alternative water resources, they respectively represent surface water ($i = 1$), groundwater ($i = 2$), imported water ($i = 3$), and reclaimed wastewater ($i = 4$)
k	various end users, water demand is divided into domestic ($k = 1$), industry ($k = 2$), public ($k = 3$), and agriculture ($k = 4$) use
PC_i	yearly cost for water production from source i , yuan
PCC_i	annualized capital cost for water production from source i , yuan
PE_i	life-cycle GHG emissions of unit volume of water production from source i , $\text{kg CO}_2\text{-eq}/\text{m}^3$
P_0	hydraulic pressure of the control node in water distribution network, Mpa
$P_{\min}$	minimum pressure required for water demand node, Mpa
POC_i	yearly O&M costs for water production from source i , yuan
r	discount rate, %
S_i	total water supply infrastructure capacities with source water i , m^3/year
t	life span of water production system, year

$UPOC_i$	O&M costs for unit volume of water production from source i , yuan/m^3
V_l	flow velocity of water in pipeline l in water distribution network, m/s
W_e	secondary effluent from wastewater treatment plant, m^3/year
wq_e	quality index of secondary effluent from wastewater treatment plant
wq_i	quality index of water withdrawn from source i
WSI_i	water scarcity index of source i
γ	leakage ration of water supply, including water lost in waterworks and distribution pipelines, %

Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.jclepro.2018.05.161>.

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